Impact of δ-rays on Single-Event Upsets in Highly-Scaled SRAMs

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Outline

- Background.
  - Brief history of radiation effects.
  - Some device basics.
  - Charge collection mechanisms and single event upset (SEU).
- Trends in advanced technology nodes.
- δ-ray Events and Simulation Methods
  - Production.
  - Interaction with material.
- Simulation results.
  - Energy Deposition.
  - Lateral range of δ-rays – “bubble of trouble.”
- Future work
- Consequences for future technology and reliability

Very Early Spacecraft Failures due to Space Radiation

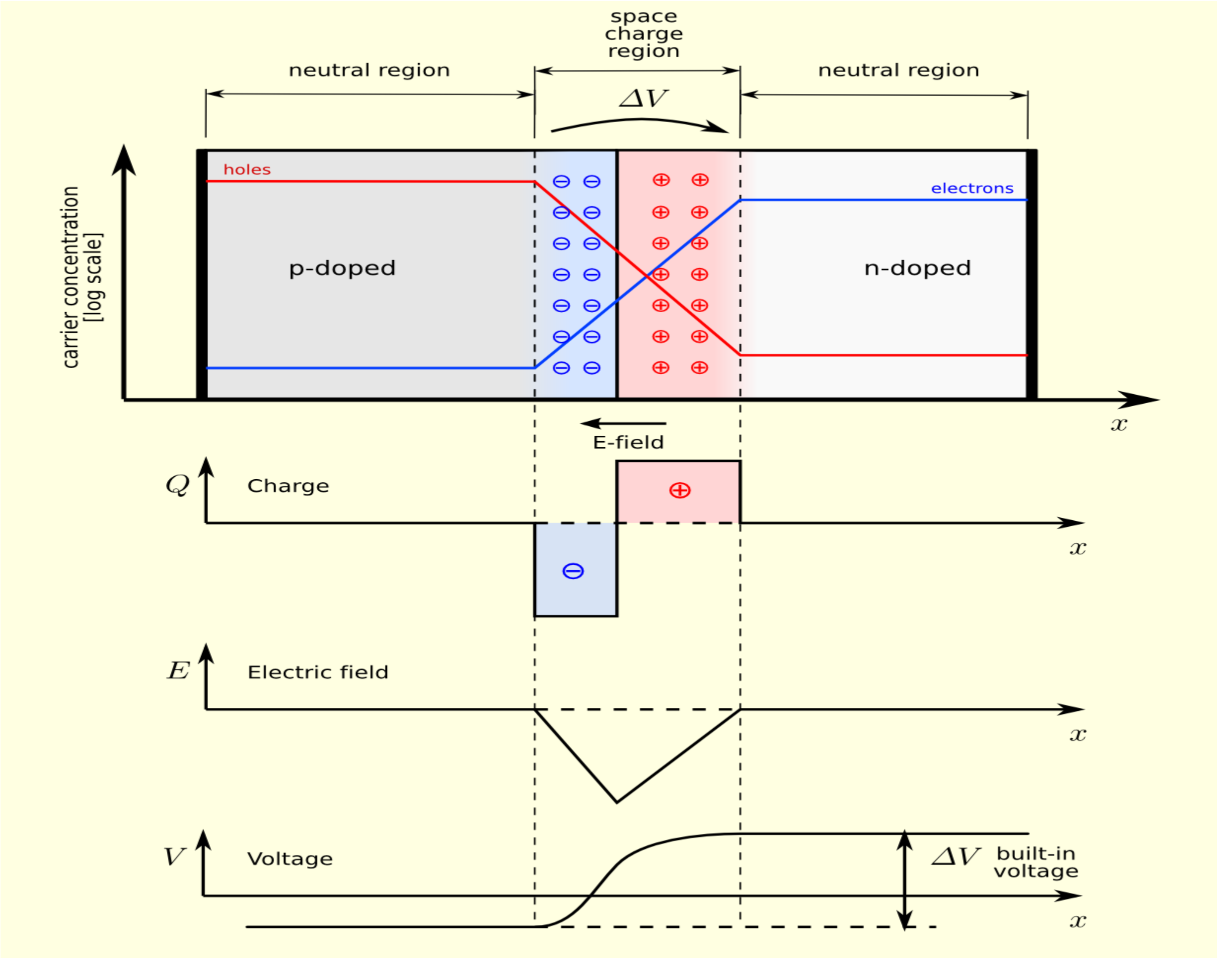
(W. E. Price, *IEEE Trans. Nucl. Sci.*, Dec. 1965)

Spacecraft	Cause of Failure
Explorer XIV	Power Supply
Explorer XV	Transistor
UK-1	Solar Power System
TRAAC	Solar Cells
Transit IV B	Solar Cells
Telstar I *	Transistor

* Failed Nov. 24, 1962, restored Jan. 3, 1963
(Mayo et al., *Bell Syst. Tech. J.* 43, 1631 (1963))

A brief description of a basic device structure.

- Simple diode structure is a p-n junction.
- Characterized by the presence of a depletion region.
- Presence of an electric field.



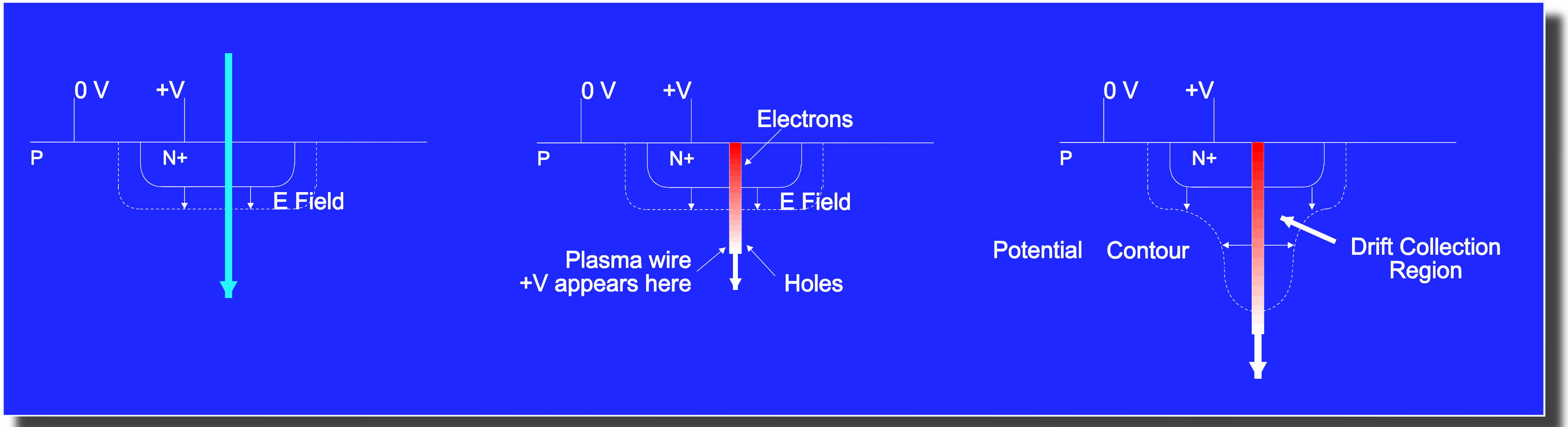
Charge collection mechanisms.

Drift (fast)

- Carriers are collected by the presence of an electric field.
- Dense column of carriers perturbs the depletion region.
  - Results in larger charge collection.

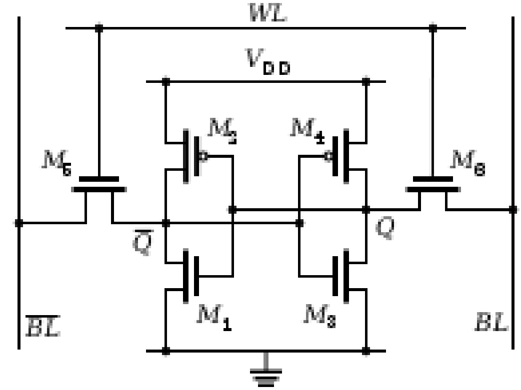
Diffusion (slow)

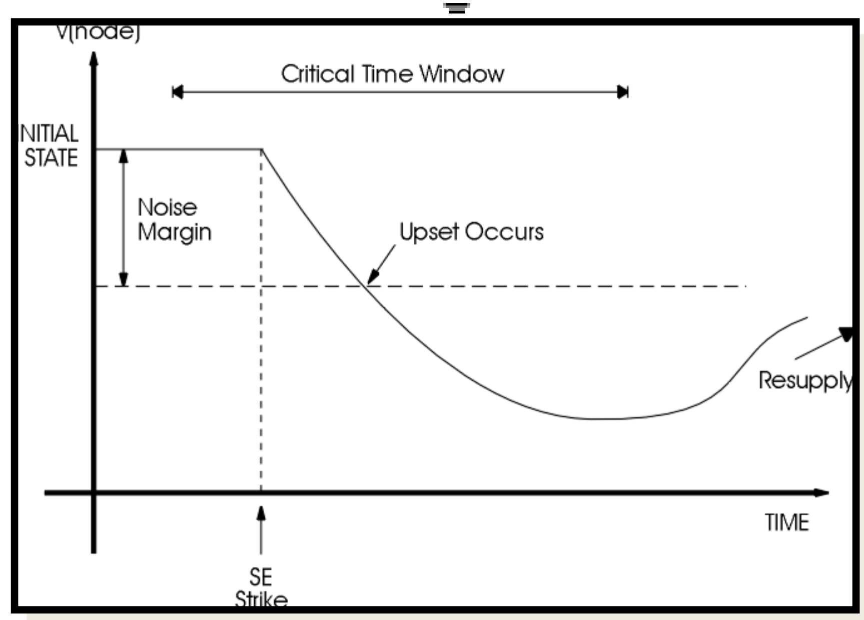
- Dense column of carriers results in a diffusion current element.
- Slower contribution to the resulting transient.



Upset mechanism for SRAMs.

- Corruption of stored information is known as an single event upset (SEU).
- Sufficient charge generated and collected to latch the output of the cross-coupled inverter element.
- Critical charge – the minimum amount of generated charge that can upset the circuit.





Energy deposition, δ-ray generation.

- Stopping power is rate of energy lost per unit path length in the material.
- The energy per mass of the particle bounds the maximum energy for δ-rays generated in the event.
- Energetic particles can produce higher energy δ-rays, their inelastic mean free path can be quite long.

δ-ray transport – track structure.

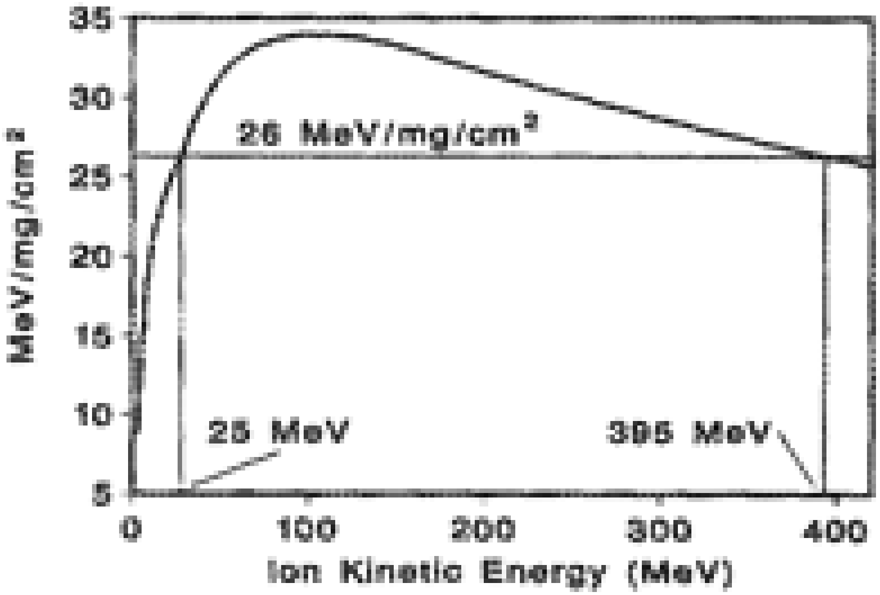


FIG. 1. Stopping power of Cu in Si.[3] Two energies (25 and 395 MeV) are indicated that yield the same stopping power [26 MeV/(mg/cm²)] at the point of entrance of a silicon target. The initial e-h pair distributions produced by such ions are not the same, even though the total charge production in a thin region of the target is the same.

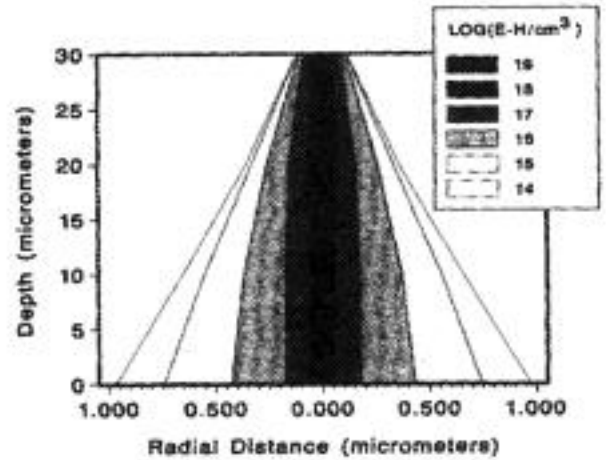


FIG. 4. Energy density contours for incident 250 MeV Fe in Si.

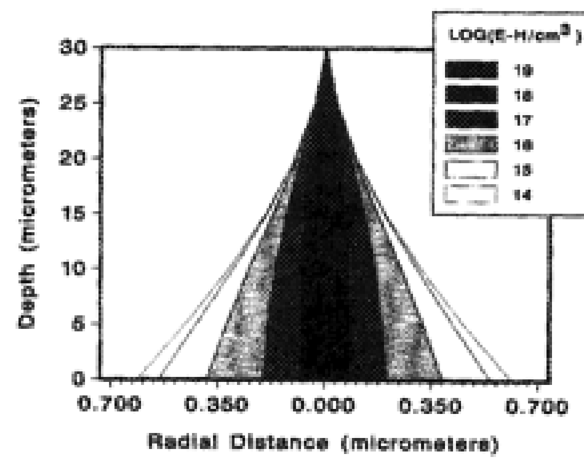


FIG. 6. Energy density contours for incident 270 MeV Kr in Si.

After Stapor, Journal of Applied Physics, 1988.

δ-ray interaction mechanisms.

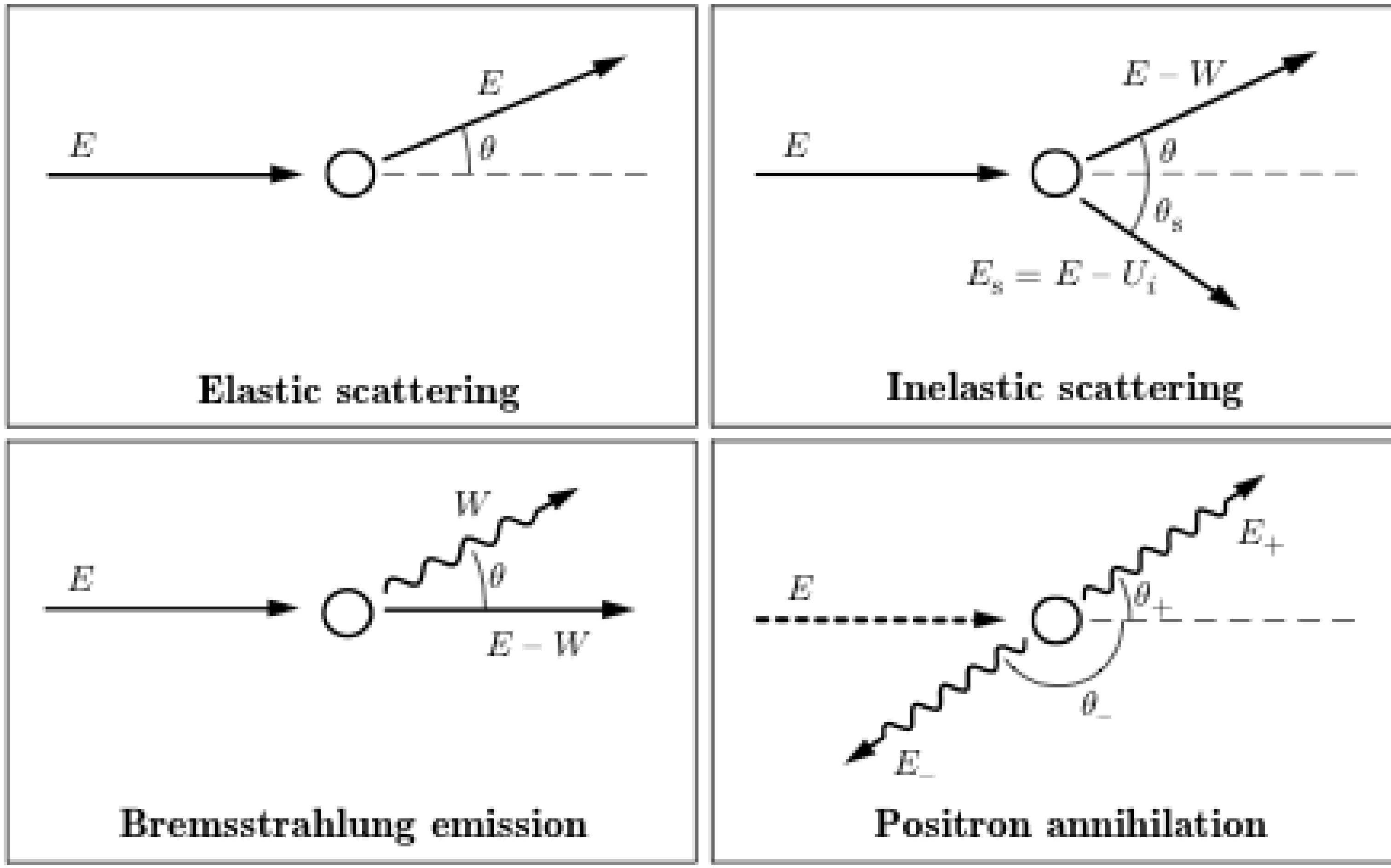


Figure 3.1: Basic interactions of electrons and positrons with matter.

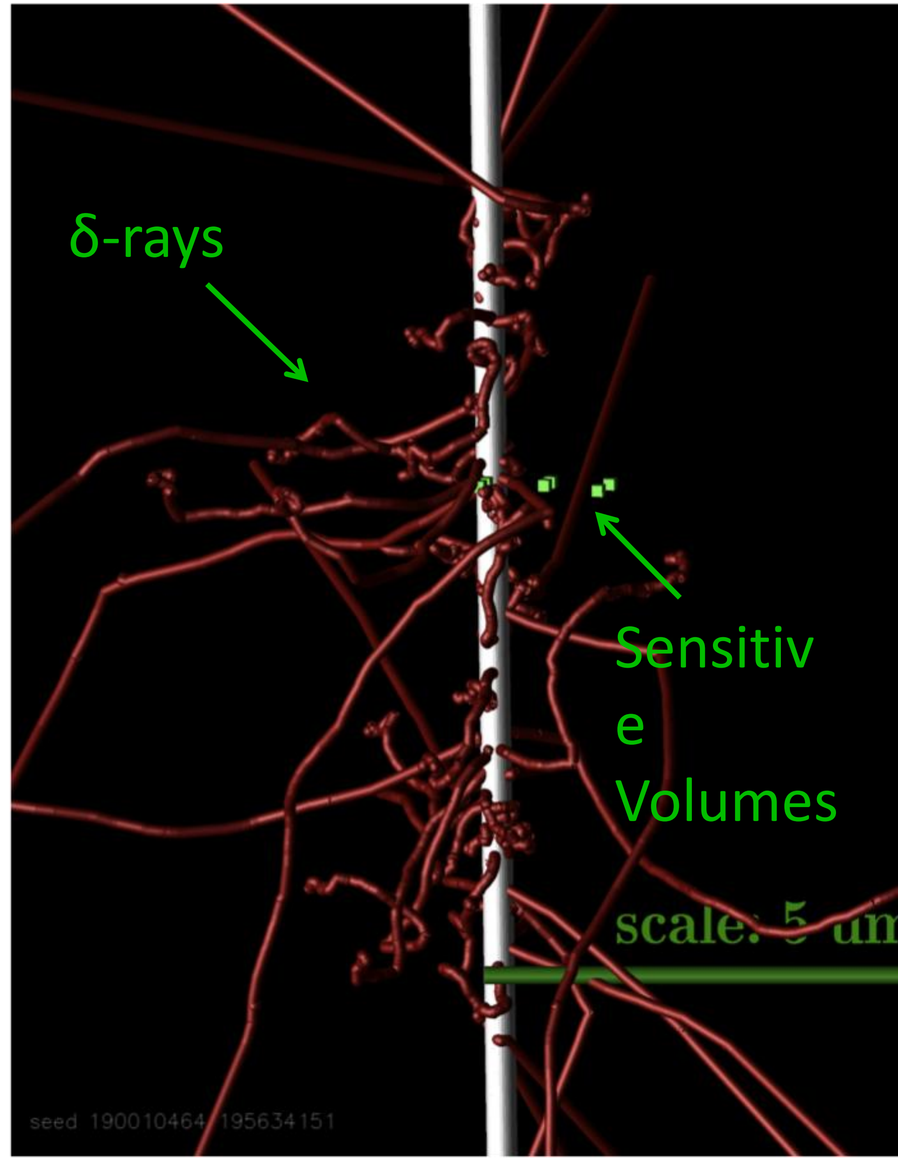
Trends in Advanced Technology Nodes

- Decreasing feature sizes are leading to an overall reduction in critical charge.
  - IBM 65 nm SOI reported to have critical charge around 0.14 fC – 0.24 fC (1500 electrons) [1].
- Recent publication from IBM details a 22 nm SOI technology node [2].
  - SRAM cell area of 0.1 μm^2.
  - Estimated critical charge of 0.08 fC, approximately 2.25 keV (500 electrons) of deposited energy in the sensitive structure of the device.

[1] Rodbell, K.P., et al, "Low-Energy Proton-Induced Single-Event-Upsets in 65 nm Node, Silicon-on-Insulator, Latches and Memory Cells," IEEE Trans. Nucl. Sci., vol.54, no.6, pp.2474-2479, Dec. 2007.
[2] Haran, B.S. et al, "22 nm technology compatible fully functional 0.1 μm2 6T-SRAM cell," IEDM 2008. vol., no., pp.1-4, 15-17 Dec. 2008.

δ-ray Events and Simulation Methods

- Utilization of Monte-Carlo Radiative Energy Deposition (MRED).
  - Geant4-based radiation transport code developed at Vanderbilt University.
  - Coupled with Penelope for accurate tracking of intermediate to low-energy δ-rays.
- Allows detailed tracking of energy deposition from δ-rays events in small, non-adjacent device volumes.

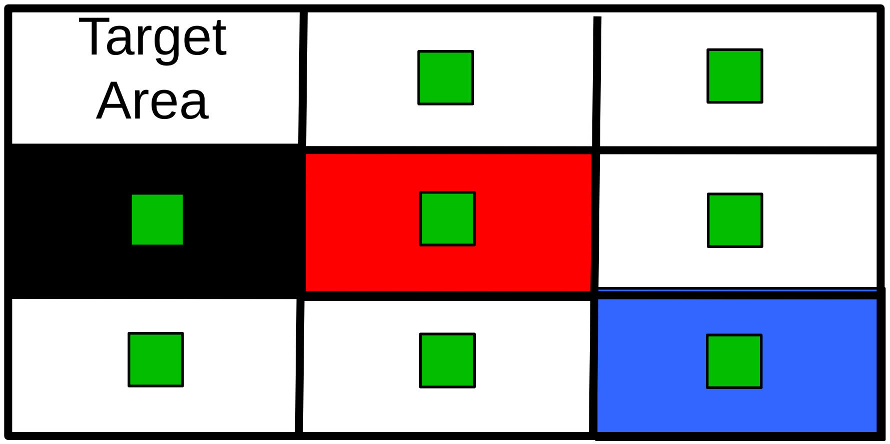


Simulated Device Structure

Simulated Structure Details

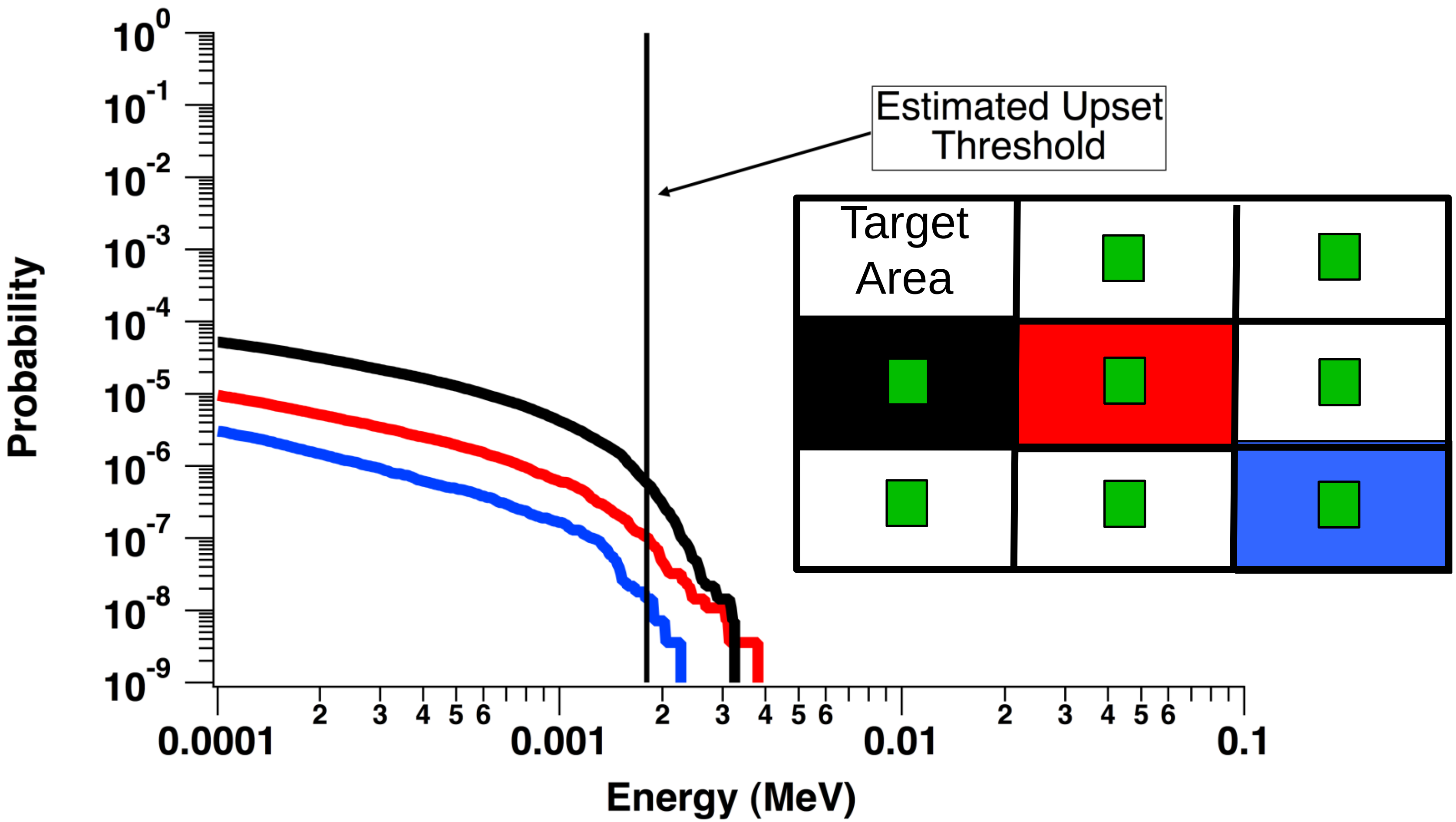
- Dimensions were chosen to be representative of advanced technology nodes.
- An array of structures was implemented with nearest neighbor cells at logarithmically scaled distances of 0.18 μm in the x-direction and 0.554 μm in the y-direction.
- Wafer size representing a realistic die structure with a thickness of 500 μm.
- Sensitive region of each cell was simulated as a single 50 nm cube.
- Cumulative probability distribution defines statistics of δ-ray upsetting a cell.

Top-Down View of Simulated Structure

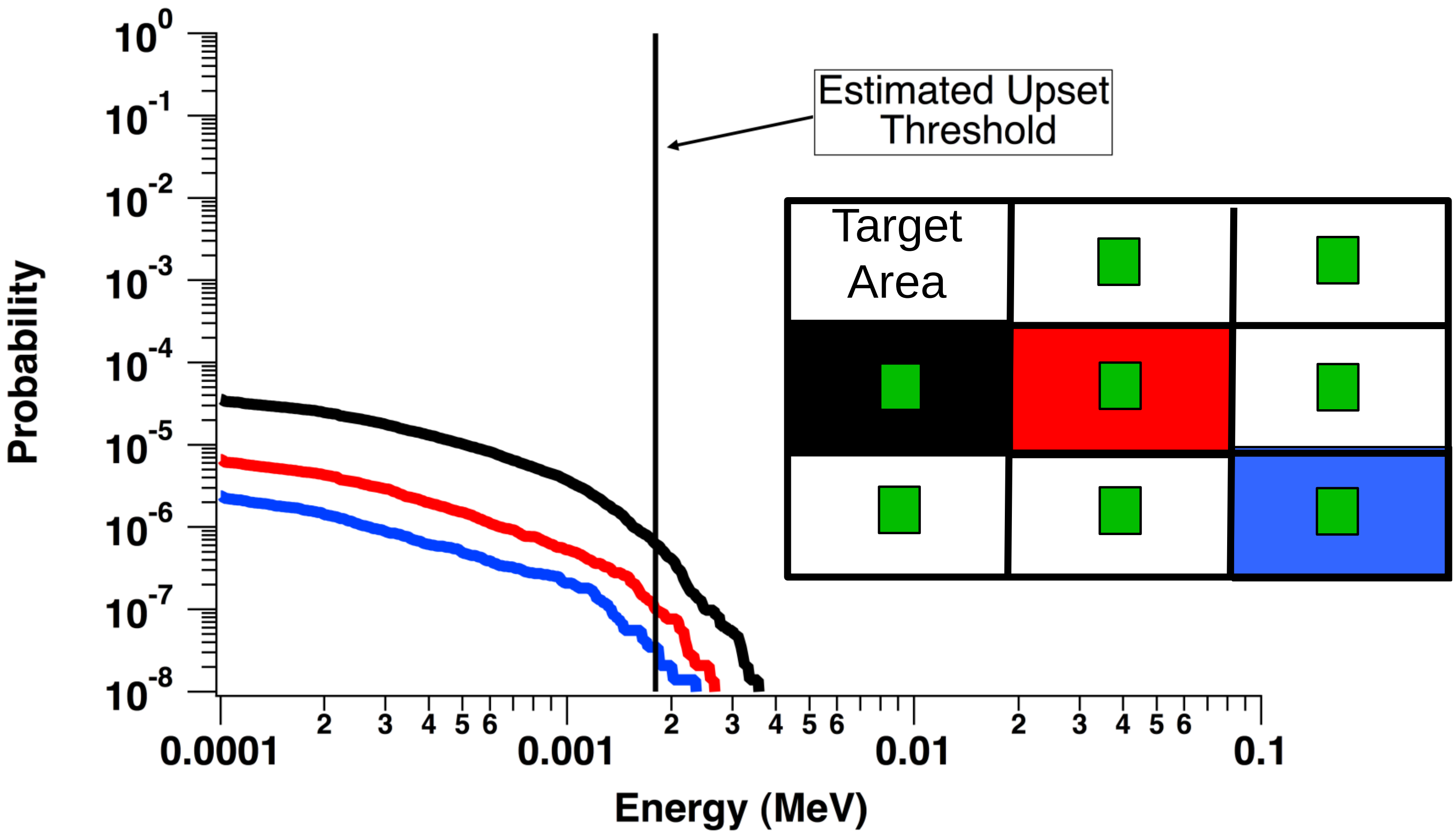


$$P(E_i) = \frac{\sum_{j \geq i}^{\infty} N(E_j)}{\sum_{j=0}^{\infty} N(E_j)}$$

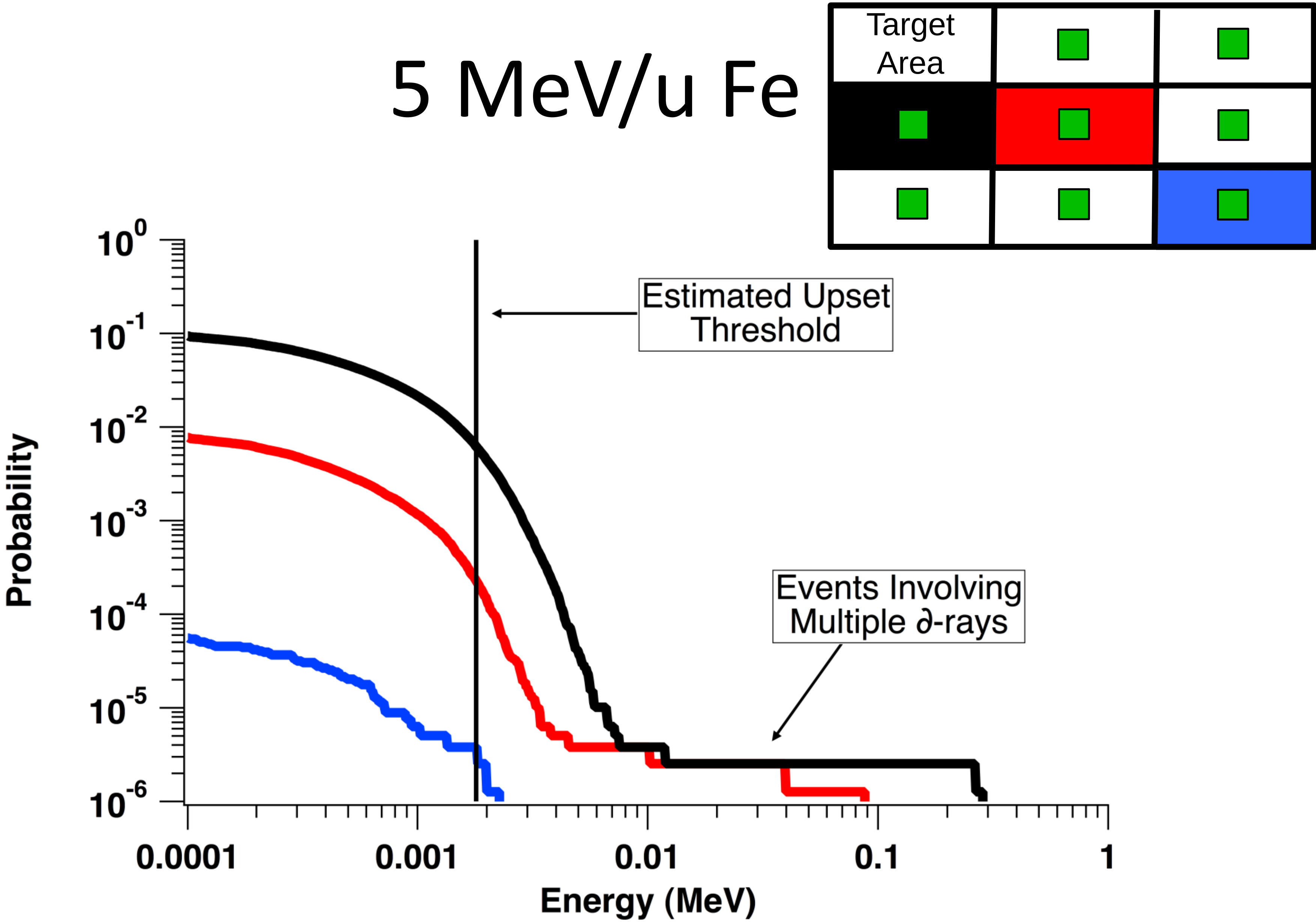
100 MeV Protons



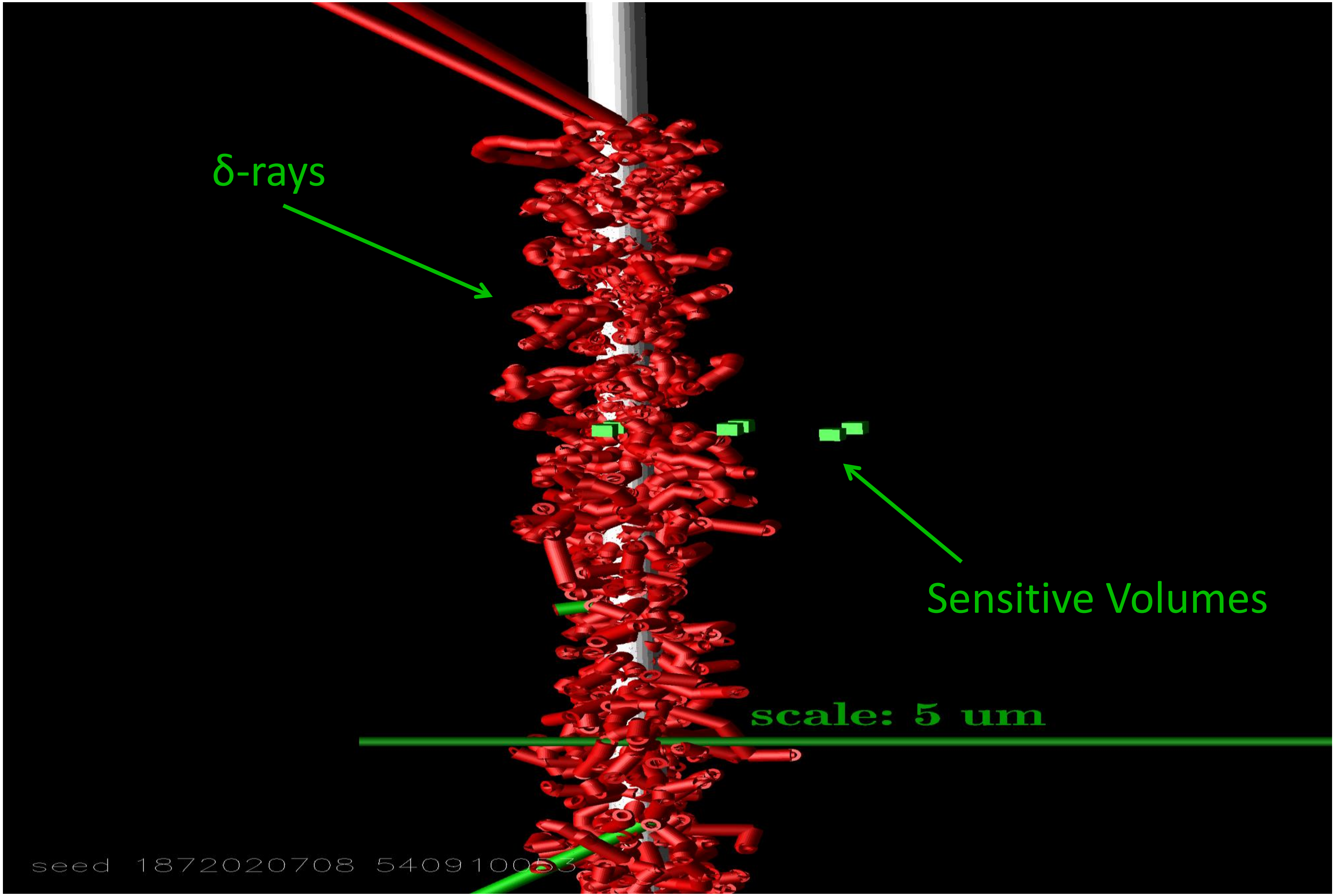
360 MeV Protons



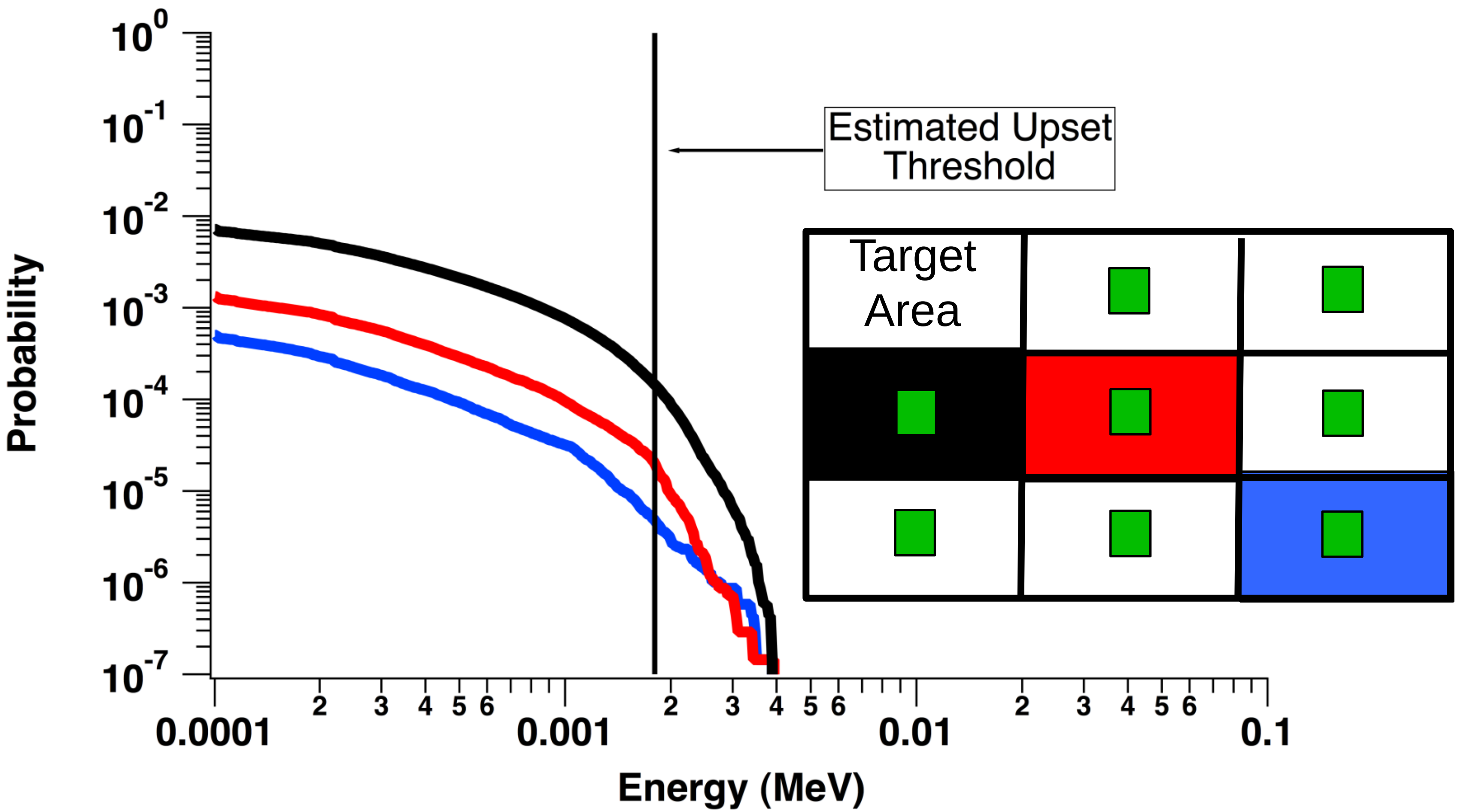
5 MeV/u Fe


Target
Area
Estimated Upset
Threshold
Events Involving
Multiple ∂-rays
Probability
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
0.0001
0.001
0.01
0.1
1
Energy (MeV)

5 MeV/u Fe Strike

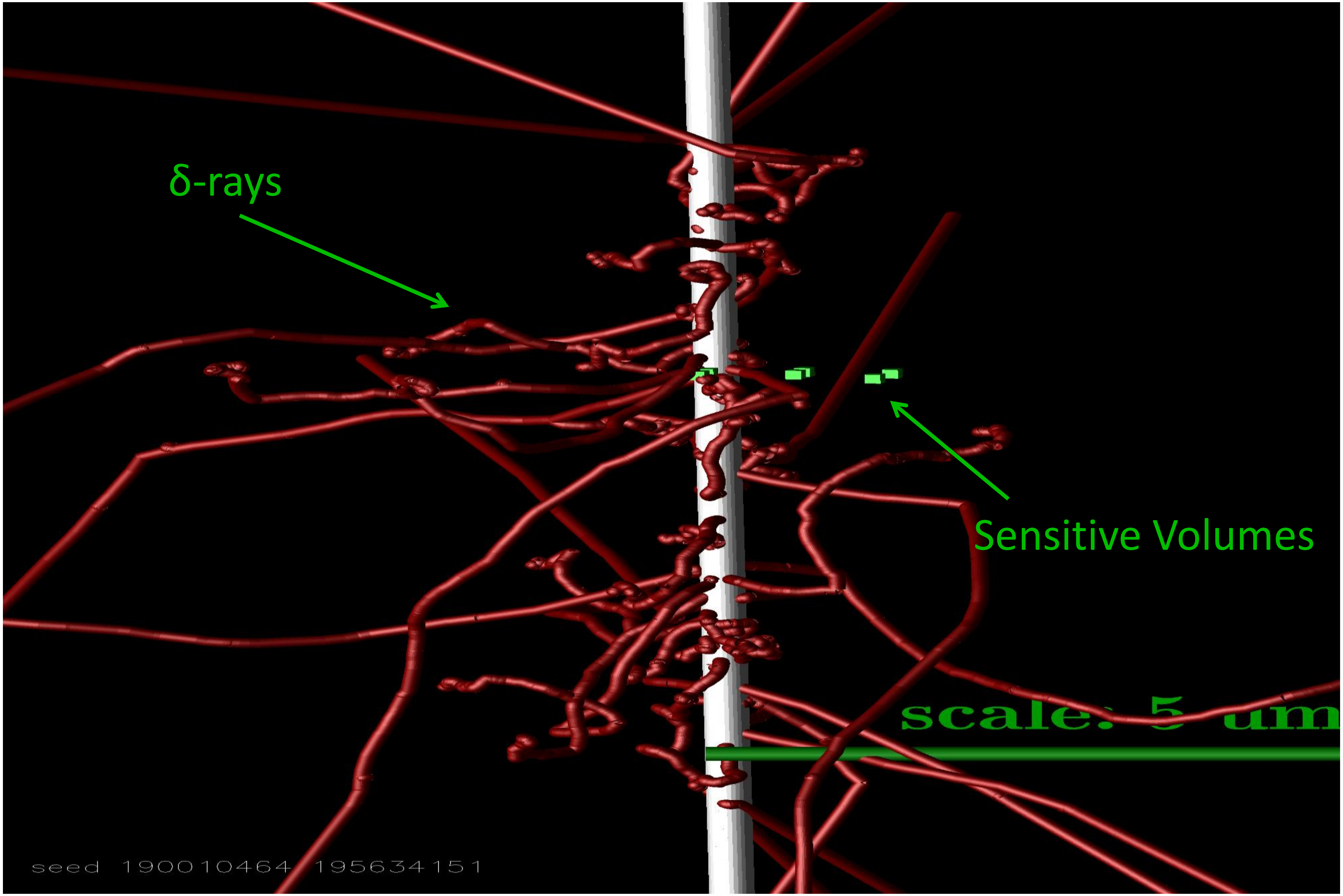


500 MeV/u Fe

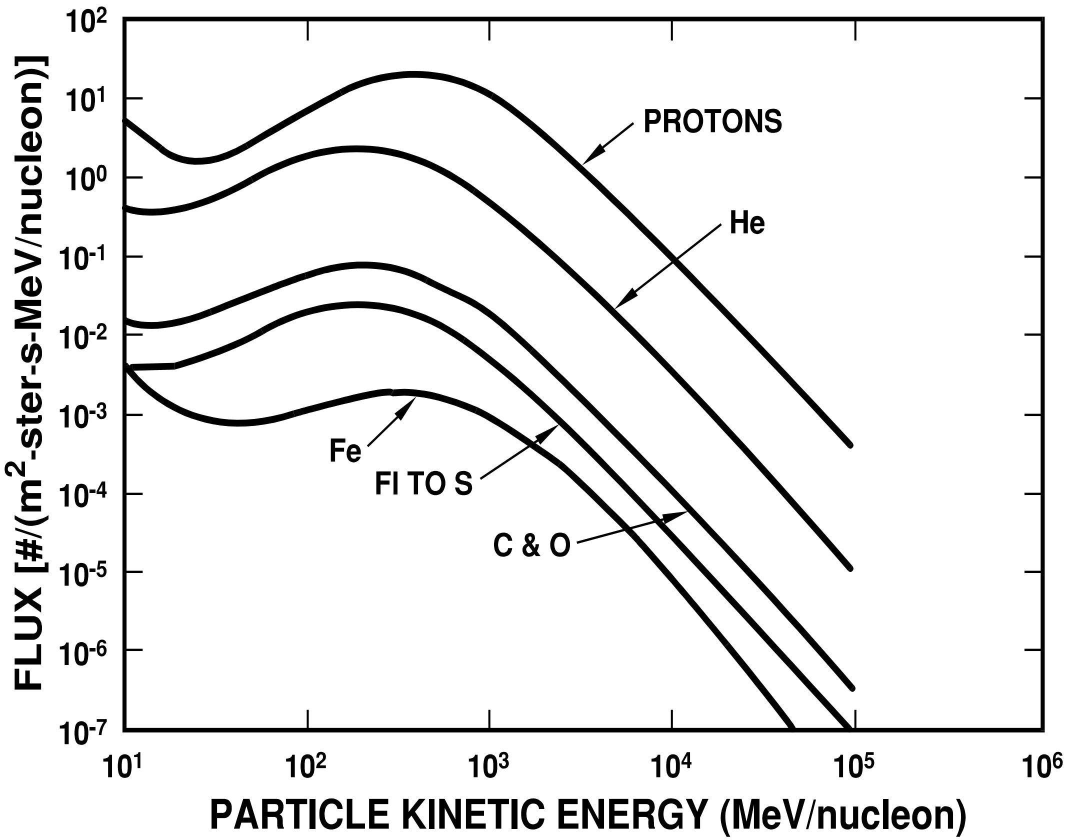


Probability
Energy (MeV)
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
0.0001
0.001
0.01
0.1
Estimated Upset Threshold
Target Area

500 MeV/u Fe Strike



ENERGY SPECTRUM OF GALACTIC COSMIC RAYS



After J. H. Adams, et al., NRL Memorandum Report 4506, August 25, 1981

- For most particles flux peaks between 100 and 1000 MeV/nucleon
- At these energies it is nearly impossible to shield electronics inside a spacecraft

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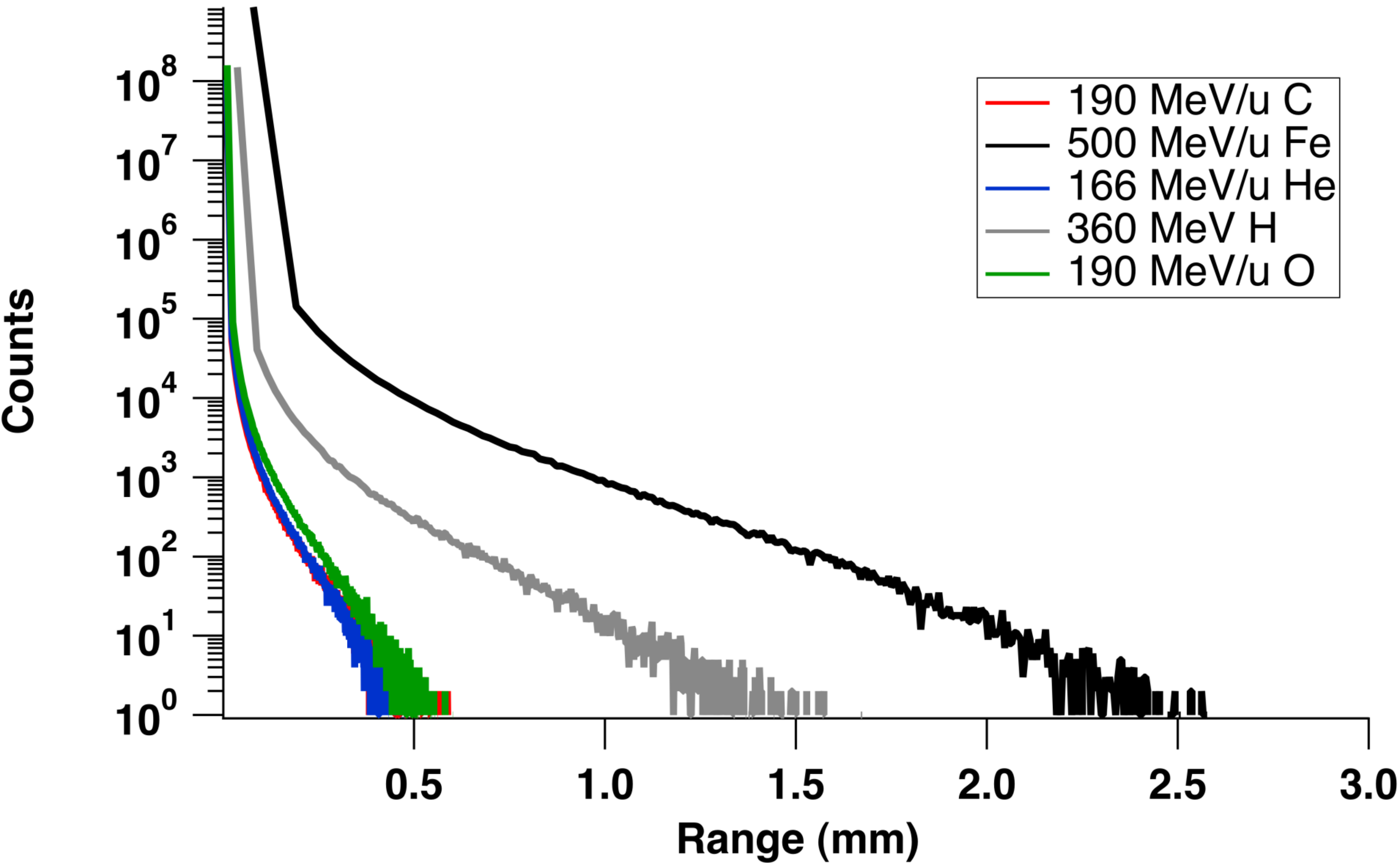
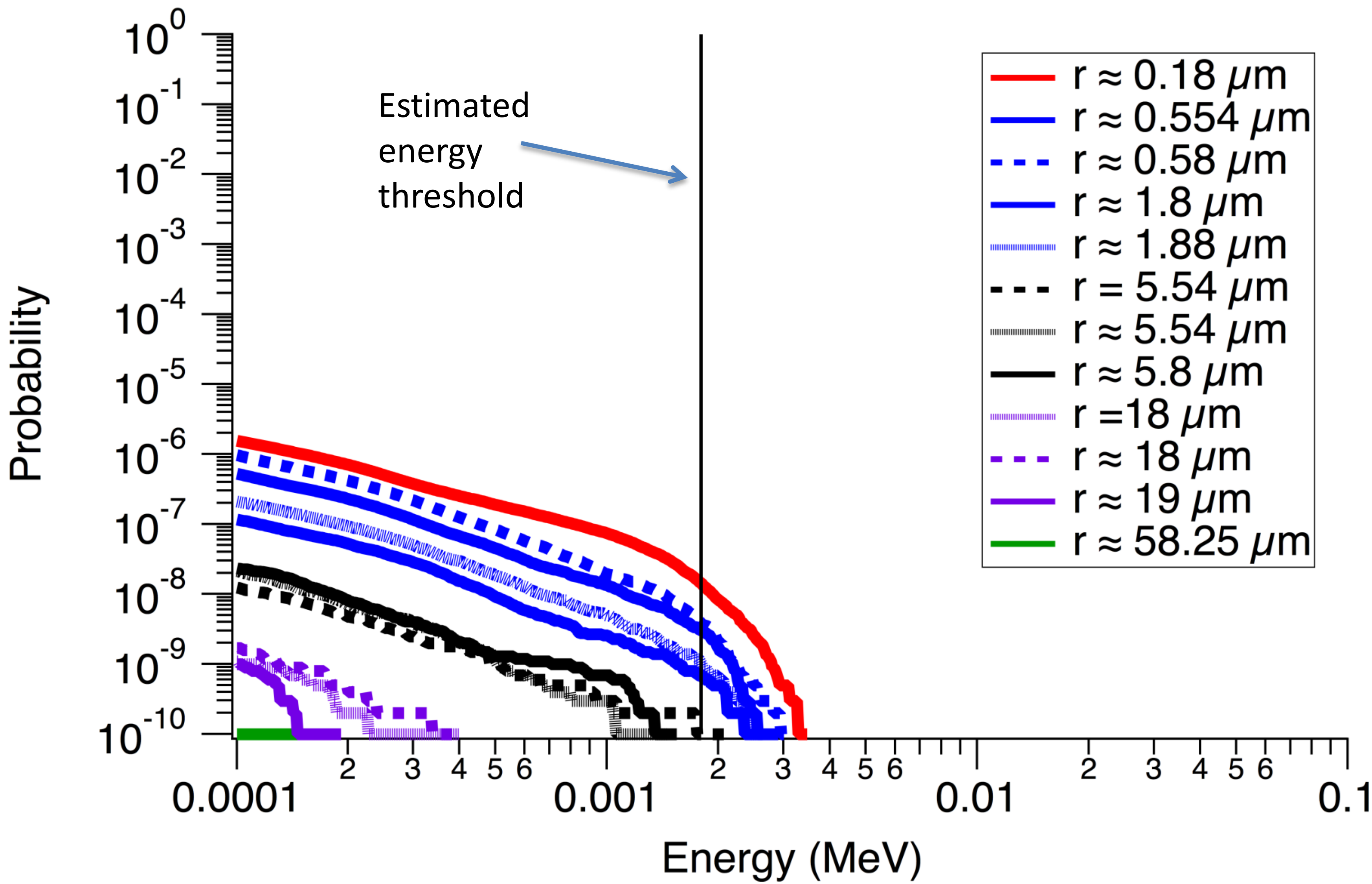
Range Chart

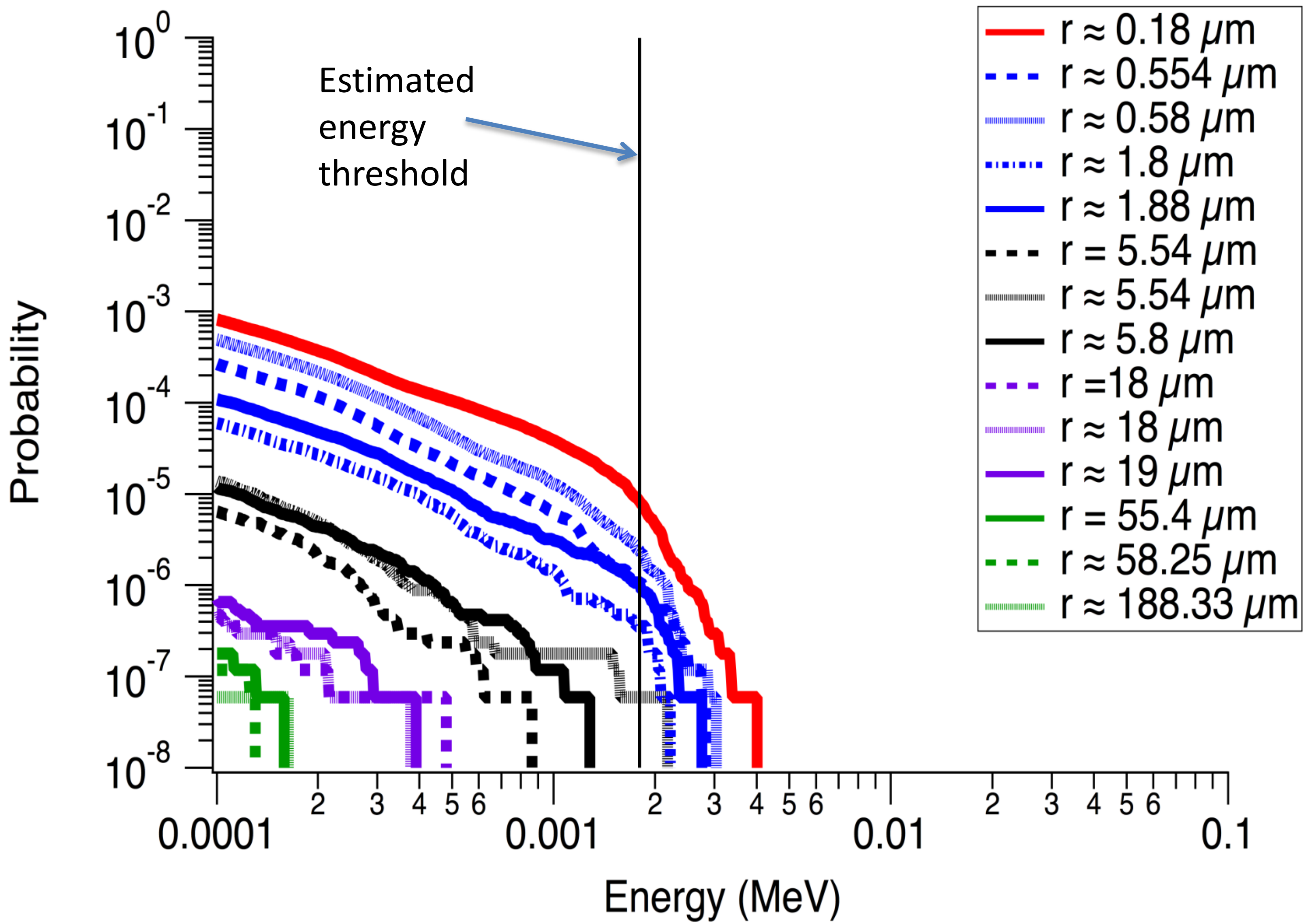


190 MeV/u C
500 MeV/u Fe
166 MeV/u He
360 MeV H
190 MeV/u O
Counts
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
0.5
1.0
1.5
2.0
2.5
3.0
Range (mm)

1 GeV Protons

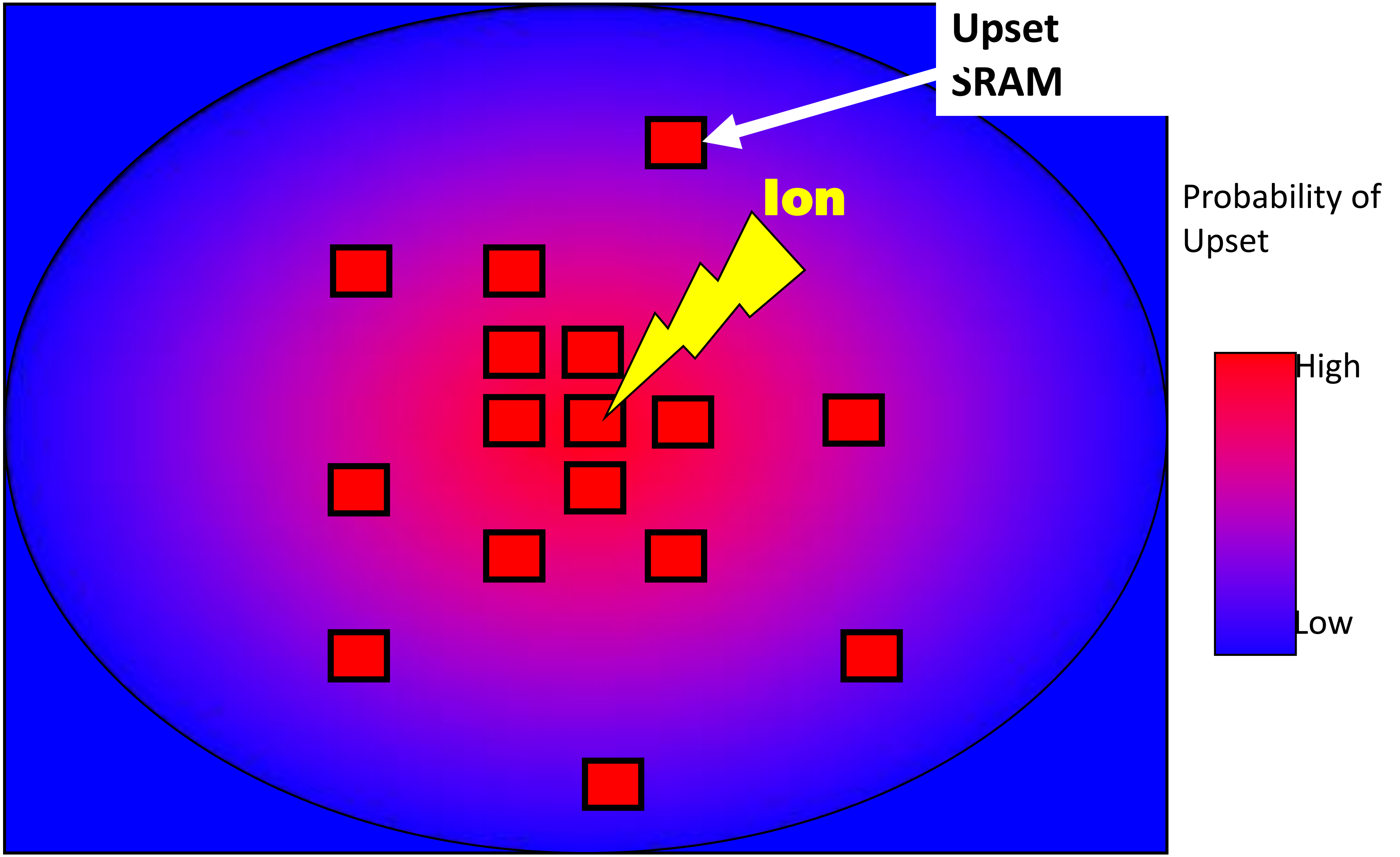


28 GeV Fe



Estimated energy threshold
Probability
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
0.0001
0.001
0.01
0.1
Energy (MeV)
r ≈ 0.18 μm
r ≈ 0.554 μm
r ≈ 0.58 μm
r ≈ 1.8 μm
r ≈ 1.88 μm
r = 5.54 μm
r ≈ 5.54 μm
r ≈ 5.8 μm
r =18 μm
r ≈ 18 μm
r ≈ 19 μm
r = 55.4 μm
r ≈ 58.25 μm
r ≈ 188.33 μm

Possible Signature of SEUs from δ-rays



Future work.

- Study the dependence on angle of incidence for the primary particle on energy deposition.
- Develop test methods to show this effect experimentally.
  - SEM/TEM/Van de Graff.
- Develop the basis of a predictive model for single event upset which includes effects from δ-rays.

Conclusions

- Advanced technology nodes are on the threshold where δ-ray events will begin to have a significant impact on SBU and MBU error rates.
- It is important to develop predictive models for mission reliability evaluation.
- A thorough understanding of the operating environment is essential for hardening techniques which rely on spatial separation of critical nodes.